PATENT SPECIFICATION

(11) 1 539 222

(21) Application No. 42137/76 (22) Filed 11 Oct. 1976
(31) Convention Application No. 643421
(32) Filed 22 Dec. 1975 in
(33) United States of America (US)
(44) Complete Specification published 31 Jan. 1979
(51) INT CL² G01V 3/18
(52) Index at acceptance
G1N 18A2A 19B2B 19B2C 19B2Q 19D11

1 539 222

(19)

(54) WELL LOGGING METHODS TO DETERMINE EARTH FORMATION DIELECTRIC CONSTANT

(71) We, TEXACO DEVELOPMENT CORPORATION, a corporation organised and existing under the laws of the State of Delaware, United States of America, of 135 East 42nd Street, New York, New York 10017, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to well logging methods for determining the electromagnetic properties of earth formations in the vicinity of a well bore hole and, more particularly, relates to well logging techniques for determining the effects of fluid invasion from the bore hole on the measurement of earth formation dielectric constant.

Recent progress has been made in the measurement of the electromagnetic characteristics of earth formations at radio frequencies. Such measurements are valuable in distinguishing fresh water bearing earth formations from oil formations in open well bore holes. For example, dual radio frequency measurements of dielectric constant and resisitivity of bore hole media are disclosed in British Patent Specification No. 1,460,186 which include the measurement of the amplitude of the total electromagnetic field at two different radio frequencies. These measurements are combined in order to simultaneously determine the resistivity and dielectric constant of the earth media surrounding the well bore hole.

While the radio frequency measurement of the dielectric constant and resistivity of earth formations in the vicinity of a well bore has proven to be very useful, particularly in areas wherein the well drilling fluid is fresh water or oil base mud, and where the earth formations surrounding the well bore are primarily fresh water filled or oil filled, these techniques have not proven to be entirely satisfactory in the case of saline drilling fluid filled well bores. Historically, the use of saline well drilling fluids has led to similar problems in the interpretation of induction and resistivity well logging measurements. These problems occur in electrical resistivity and induction logging measurements due to the invasion of highly porous earth formations by the drilling fluid from the bore hole. This bore hole fluid "invades" or penetrates the highly porous formations to some depth which is functionally related to the porosity, water and oil saturation of the formations and the permeability of these earth formations.

The effect of the invasion of conductive bore hole fluids into the invaded zone surrounding the bore hole in highly porous and permeable earth media leads to the masking of the true resistivity of the "virgin" or uninvaded formations in the vicinity of the bore hole. Because of this invasion problem, in the past resistivity and induction logging apparatus has been designed in proliferation in order to be able to measure and distinguish the effects of the invasion fluid on the resistivity of the earth formations in the vicinity of the bore hole.

Focused induction logging instruments and resistivity measuring electrode instruments having different radial depths of investigation from the bore hole into the earth media surrounding the bore hole have been produced. Such instruments have been used in an attempt to measure the resistivity of the invaded zone (usually labeled R_{xo}) and the resistivity of the virgin or uninvaded formations (usually labeled R_t).

At the radio frequencies of interest with respect to radio frequency induction dielectric well logging the conductivity of the earth formations surrounding the bore hole is, in principle, intimately related to the measurement of the dielectric constant of the earth formation surrounding the well bore. Due to the possible "screening

effect" of a conductive medium on the electromagnetic waves which are propagated from the transmitter coil of such a measurement system the amplitude of induced currents in the receiver coil or coils of such a system can be affected. If an amplitude measurement alone is relied on, as in the example of the previously mentioned patent, this screening effect can influence the received amplitude of the electromagnetic field at the receiver coils due to the attenuation of the transmitted signal. If the magnitude of the received signal is minimized by the effects of invasion, then it is apparent to one skilled in the art that it is more difficult to make the measurement with a small amplitude signal than it would be with a larger amplitude signal at the receiver coils.

Similarly, in the derivation of the theory of measurement of the dielectric constant at radio frequencies, it may be shown that both the resistivity and dielectric constant of the invaded earth formations affect the total field amplitude or relative phase shift of the electromagnetic field induced in the receiver coils by a transmitted signal from a radio frequency transmitter. Hence, both the resistivity and dielectric constant of the invaded zone must be accurately known in order to determine accurately the dielectric constant of the virgin formation earth material surrounding the bore hole. The foregoing patent offers techniques for simultaneously determining both the resistivity and dielectric constant of the earth media in the vicinity of the bore hole. However, these techniques do not take into account the effects due to the invasion phenomena.

According to the present invention there is provided a method for determining the dielectric constant ε_{xo} of the invaded zone and the dielectric constant ε_t of the uninvaded formations in respect of earth formations invaded by conductive drilling fluid from a well borehole, said method comprising:

determining by induction and resistivity well logging the resistivity R_{xo} of the invaded zone, the resistivity R_t of the uninvaded formation and the radial depth of invasion d_i, all at a determined depth in the well bore;

transmitting electromagnetic waves at a frequency in the range of 10 to 60 megahertz from a transmitter coil in the borehole;

measuring the phase shift of said waves between the two coils of a first pair of spaced receiver coils at a first longitudinal distance from said transmitter coil and generating a signal θ_s representative thereof, said first distance providing a first radial depth of investigation substantially in said invaded zone;

measuring the phase shift of said waves between the two coils of a second pair of spaced receiver coils at a second longitudinal distance from said transmitter coil and generating a signal θ_L, said second distance being greater than said first distance to provide a second radial depth of investigation substantially in said uninvaded formation; and

for said set of determined resistivity R_{xo}, resistivity R_t and invasion depth d_i, correlating the signals θ_s and θ_L to derive indications of the dielectric constants ε_{xo} and ε_t at said depth.

An embodiment of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:—

Figure 1 is a schematic diagram illustrating a well logging system used in the present invention.

Figure 2 is a graphical relationship illustrating the derivation of the dielectric constant of the invaded zone and the virgn formation as measured by phase shift differences between a short spaced and long spaced coil pair of radio frequency dielectric induction coils.

Figure 3 is a schematic illustration of the coil spacing of the radio frequency dielectric induction logging portion of the well logging system of Figure 1.

Induction and electrical resistivity logs have proven useful in the past in determining earth formation resistivity and thereby locating oil bearing sands in the vicinity of a well bore hole. However, due to the fact that fresh water sands and oil sands have similar high resistivities, these logs cannot always adequately detect the difference between oil and fresh water (or slightly saline water) filling the pores of the earth formations in the vicinity of the bore hole. As disclosed in the previously mentioned patent, no 1,460,186 however, the possibility exists at radio frequencies of measuring simultaneously the formation electrical conductivity and formation permitivity (or dielectric constant) which can provide a means for distinguishing these types of liquid bearing strata. Hydrocarbons have a characteristically low dielectric constant ε_r less than 5. On the other hand, fresh water has a relatively high dielectric constant ε_r approximately equal to 80. The permitivity of a material ε is defined as the natural electrical polarization of this material. In the foregoing and following descriptions, the terms relative permitivity and dielectric constant are used synonymously. The permitivity ε is related to the permitivity of

free space ε_0 by the relationship given in equation 1:

$$\varepsilon = \varepsilon_r \varepsilon_0 \qquad (1)$$

where ε_0=8.854 picofarads per meter, the permitivity of free space.

As previously discussed the invasion of conductive well bore fluid during the drilling operation into highly porous and permeable media in the vicinity of the bore hole forms the area known as the invaded zone. In the invaded zone some of the hydrocarbon or other interstitial liquid filling the pore spaces of the earth media has been replaced by the highly conductive drilling fluid. This alters the electrical resistivity characteristics of the invaded zone and also influences the measured dielectric constant of the invaded zone. In order to apply the principles of radio frequency dielectric induction logging in order to obtain a knowledge of the fluid content of the pore spaces of the media surrounding the bore hole, it is highly desirable to accurately know the depth of invasion d_i and the electrical resistivity R_{xo} (or conductivity) of the invaded zone.

A particularly suitable measurement of the depth of investigation e_i, the electrical resistivity of the invaded zone R_{xo}, and the resistivity of the virgin formation R_t, has been provided in the past by obtaining measurements of these quantities with a well logging system sometimes known as the "dual induction laterolog".

For an understanding of the operating principles of the "dual induction laterolog" system in determining R_t, R_{xo} and d_i reference may be had to "Schlumberger Log Interpretation", Volume 1 *Principles*, and Volume 2 *Applications* both of which are published by Schlumberger Limited, 277 Park Avenue, New York, New York 10017. It will suffice to state herein that dual induction logging signals are developed by this instrument which indicate the conductivity (resistivity) of the earth formation at two different radial depths from the well bore into the formation. This information is combined with a resistivity "laterolog" measurement to yield the three quantities of interest with respect to the present invention.

The theory of radio frequency dielectric induction logging is explained with more particularly in U.S. Patent 3,891,916.

It will suffice herein to state that if the electromagnetic field theory equation of the influence of a time varying electromagnetic field generated in the well bore hole upon any currents induced in the formation surrounding the well bore hole is analyzed, that it is possible to derive the dielectric constant of the invaded zone ε_{xo} and the virgin formation ε_t by measuring the relative phase shift of the electromagnetic field between two receiver coils at two different longitudinally spaced distances from a transmitting coil located in the well bore hole.

Generally speaking, the distance from the transmitting coil to the spaced receiving coils will influence the relative depth of investigation. In general, the longer this distance between the transmitting coil and the receiving coils the deeper will be the relative depth of investigation into the media surrounding the bore hole. By combining the relative phase shift information with the "dual induction laterolog" measurements of R_{xo}, R_t and d_i the quantities of interest in the present system may be determined.

Further, if a knowledge of ε_t the true formation dielectric constant is obtained, this allows one to calculate the relative amount of oil in the virgin formation. A knowledge of the invaded zone dielectric constant allows the calculation of the irreducible oil saturation of that zone. Having both the invaded zone dielectric constant ε_{xo} and the virgin formation dielectric constant ε_t it may be shown that a direct measurement of the percentage of movable oil in the formation is given by the expression of equation (2):

$$\%\ \text{movable oil} = \frac{\varepsilon_{xo}^k - \varepsilon_t^k}{\phi(\varepsilon_w^k - \varepsilon_o^k)} \times 100$$

In equation (2) ε_{xo} is the invaded zone dielectric constant, ε_t is the virgin formation dielectric constant, ε_w is the dielectric constant of water, ε_o is the dielectric constant of oil, ϕ is the porosity and k is a formation matrix cementation factor which may be empirically derived.

If it is assumed that the depth of invasion d_i, the resistivity of the invaded zone R_{xo}, and the resistivity of the virgin formation R_t, are known, then it is possible to construct, on the basis of theoretical calculations or calibration curves from known conditions in test bore holes, a plurality of charts or graphs of the nature of that illustrated in Figure 2 of the application.

Referring now to Figure 2, a cross-plot of the relative phase shift at a short spaced pair of receiver coils and a long spaced pair of receiver coils from a radio frequency transmitter coil is illustrated for an operating frequency of 30 megahertz. It will be observed from Figure 2 that a family of roughly parallel curves are formed in this cross-plot for different values of ε_{xo} and ε_t for a given set of parameters R_t, R_{xo} and d_i. Of course, for each different set of resistivity and depth of invasion characteristics, a

different family of parallel (or roughly parallel) curves are generated on a cross-plot analogous to the cross-plot of Figure 2. The specific example of Figure 2 is shown for illustrative purposes only. For example, in a practical measurement situation, a set of such cross plots would be generated for approximately 20 different values of R_t approximately 10 different values of R_{xo}, and approximately 10 different values of d_i. Considering all the permutations and combinations of these parameters then, approximately 2,000 such cross-plots would be required to cover a practical range of conditions to be encountered in well bore holes.

The data of such cross-plots, whether theoretically or empirically derived, may be stored in a tabular form in the memory of a general purpose digital computer such as that which will be described subsequently with respect to Figure 1. Appropriate interpolation techniques may then be utilized to extract the values of ε_{xo} (dielectric constant of the invaded zone) and ε_t (dielectric constant of the virgin formation) once the values of R_t, R_{xo}, and d_i are known for a particular region of the well. A small general purpose digital computer can be programmed in an appropriate compiler language such as FORTRAN to perform the necessary calculations to determine ε_{xo} and ε_t. Similarly, the percentage of movable oil from equation 2 may then be obtained. Such a small general purpose machine could be, for example, a PDP 12 computer as furnished by the Digital Equipment Corporation of Cambridge, Massachusetts.

From the foregoing discussion and consideration of the graphical relationship of Figure 2, it is seen that if a simultaneous measurement is used to provide a measurement of R_t, R_{xo}, and d_i, then the dielectric constant of the invaded zone and the virgin formation may be accurately determined by the measurement of the relative phase shift of the radio frequency electromagnetic field at two sets of longitudinally spaced coils in a well bore hole. A system which is suitable for obtaining such relative phase shift measurements while simultaneously obtaining measurements of R_t, R_{xo} and d_i is illustrated schematically in Figure 1.

Referring now to Figure 1, a well bore hole 10 filled with a drilling fluid 11 is shown penetrating earth formations 12. An invaded zone 13 (delineated by the dotted lines) is formed by the invasion of conductive well fluid 11 from the bore hole into the porous and permeable formations surrounding it. The virgin formation material 12 has a characteristic resistivity R_t and a characteristic dielectric constant ε_t which have been relatively uneffected by the drilling operation. However, the invaded zone 13 has a different resistivity R_{xo}, and dielectric constant ε_{xo} to a depth d_i away from the bore hole, due to the invasion of this zone by the conductive well fluid. A well logging sonde 14 is shown suspended in the bore hole 10 by means of an armored well logging cable 15 which is typically spooled on the surface on a drum or spool (not shown).

The well logging cable 15 passes over a sheave wheel 16 which may be electrically or mechanically coupled to other surface equipment as indicated by the dotted line 17 to provide depth information of the location of the sonde 14 in the bore hole to the surface equipment. This depth information allows depth correlation of the electrical measurements made in the bore hole from the instrumentation carried by the sonde 14 and allows this information to be used in the manner to be subsequently described to determine R_{xo}, R_t, ε_{xo}, ε_t and d_i. The well logging cable 15 contemplated for use with the present invention may typically comprise an armored tri-axial (or armored co-axial) cable having a single centric conductor insulated from a surrounding conductive shield layer of material. The shield layer is in turn insulated from the outer or double armor layer surrounding the cable core. It will be appreciated by those skilled in the art, however, that armored multi-conductor well logging cable may be utilized in the practice of the present invention if desired.

The downhole sonde comprises a fluid tight, hollow body 14 preferably constructed of a non-conducting material, such as fiberglass, and having a central mandrel portion thereof 18 which is also constructed of a non-conductive material such as fiberglass. The upper end of the sonde is equipped with a telemetry system 19 for transmitting signals from the downhole sonde to the surface equipment. Just below the telementary system 19 is located a "dual induction laterolog" arrangement 20. The details of this are not shown in the drawing of Figure 1, but may be had by reference to the previously referenced Schlumberger Well Log Interpretation Manuals.

Below the portion 20 of the instrument (and shown in more detail) is the radio frequency induction dielectric log portion of the instrument. The radio frequency induction dielectric log portion of the instrument includes receiver electronics (illustrated schematically at 21) which are associatad with two pairs of longitudinally spaced receiver coils labeled R_1, R_2, R_3 and R_4 in Figure 1. A single transmitter coil labeled X is also provided in the induction

dielectric log portion of the system. A transmitter electronics portion 22 (which is illustrated only schematically in Figure 1) is powered by a battery 23 which is carried at the lower end of the sonde 14. Details of this transmitter electronics may be had by reference to U.S. Patent 3,891,916. While the frequency range of interest for making the measurements of the present invention is from 10 to 60 megahertz, the transmitter illustrated in the embodiment of Figure 1 is preferably operated at a frequency of about 30 megahertz.

Referring now to Figure 3, the coil spacings of the radio frequency dielectric log portion of the sonde in Figure 1 are illustrated in more detail. The transmitter coil X is spaced approximately 10 inches from receiver coil R_1. Receiver coils R_1 and R_2 are spaced approximately 6 inches apart. This spacing configuration allows receiver coils R_1 and R_2 to sense a phase shift which is primarily influenced by the invaded zone of the earth formations surrounding a typicaly sized well bore hole. Receiver coil R_3 is situated approximately 30 inches from the transmitter coil X and receiver coils R_3 and R_4 are spaced approximately 12 inches apart as illustrated in Figure 3. This spacing configuration allows the relatively phase shift of the electromagnetic field measured between receiver coils R_3 and R_4 to be primarily influenced by the characteristics of the virgin formation zone of Figure 1.

Referring again to Figure 1, the portion of the figure shown in the dotted box 21 to the right of the downhole sonde corresponds to the receiver electronics portion 21 illustrated schematically on the sonde itself. This instrumentation is used to derive a measurement of the relative phase shift of the electromagnetic fields produced by the transmitter signal in the earth formations adjacent to the well bore hole. The measurement of the relative phase shift angle of the electromagnetic field between the respective coils of each of the two pairs of longitudinally spaced receiver coils are made in precisely the same manner. Therefore, a detailed description of the measurement of the relative phase shift between only one pair of the coils will suffice to explain the operation of the system.

The time varying electromagnetic field induced in receiver coil R_1 is coupled to a pair of gain controlled amplifiers 24 and 25. Similarly, the time varying electromagnetic field induced in receiver coil R_2 is coupled to a pair of gain controlled amplifiers 26 and 27. The gain of amplifier stages 24 and 25 is controlled by a feedback signal coupled through AGC (Automatic Gain Control) amplifier 28 which samples a portion of the output signal of amplifier 25 and uses this to generate a gain control signal which keeps approximately a constant output level signal from the amplifier stage 25. Similarly, AGC amplifier 29 samples a portion of the output signal of amplifier stage 27 and supplies a gain control signal to control the gain of amplifier stages 26 and 27 to produce approximately a constant output.

The approximately sinusoidal wave form output from amplifier stage 25 is coupled to a Schmitt trigger circuit 30. This circuit comprises an emitter coupled logic gate having a very steep rise time. The Schmitt trigger circuit 30 thus transforms the approximately sinusoidal output of the amplifier stage 25 to a very sharp sided square wave form. Similarly, the approximately sinusoidal output of amplifier stage 27 is coupled to a second emitter coupled logic 31 which is also employed as a Schmitt trigger. Similarly this circuit shapes this waveform into a very steep sided approximately square wave pulse. The output of Schmitt triggers 30 and 31 are supplied as inputs to an exclusive NOR gate 32 which is also an emitter coupled logic circuit having a very fast response time. The action of exclusive NOR logic gate 32 is to produce an output voltage pulse whose duration is proportional to the relative phase shift of the electromagnetic field between the receiver coils R_1 and R_2. This signal is supplied to a conventional intergrator circuit 33 which integrates this square wave form to produce an output voltage θ_s which is proportional to the relative phase shift of the electromagnetic field between the receiver coils R_1 and R_2.

A voltage controlled oscillator (VCO) 34 is supplied with the output of the integrator 33. The operational frequency of VCO 34 is determined by the magnitude of the voltage input θ_s. This voltage controlled oscillator 34 thus produces a frequency modulated signal between two previously chosen limits of frequency which is representative of the relative phase shift of the electromagnetic field between receiver coils R_1 and R_2. This signal is supplied to a summing amplifier 35 where it is summed with a corresponding frequency modulated signal θ_L between two different frequency limits. This θ_L signal corresponds to the relative phase shift of the electromagnetic field between the longer spaced receiver coil pair R_3 and R_4. Thus, the output of summing amplifier 35 comprises a signal comprising a pair of frequency modulated signals θ_s and θ_L which is supplied to the line driver circuitry in the telemetry section 19 of the downhole equipment.

Similarly, the measurement signals from the portion 20 of the downhole sonde which

are representative of R_t, R_{xo} and d_i are supplied to the telemetry section 19 for transmission to the earth via well logging cable 15.

The foregoing description of the downhole equipment has neglected to describe in detail the power for the operation of the telementary portion 19, the portion 20 and the receiver electronics portion 21 of the instrument because these power supplies may be of conventional types known in the art. Operative power for the downhole equipment, except for the transmitter portion 22 thereof, is supplied from a surface power supply source 37 via the well logging cable 15.

At the surface the frequency modulated component signals from the well logging cable center conductor 38 are supplied to a plurality of separator circuits 39, 40, 41, 42 and 43. These circuits may comprise, for example, high Q bandpass filter circuitry which is capable of effectively filtering each of the five component signals from the sum signal which is present on the cable conductor 38. The five separate signals representative of R_t, R_{xo}, d_i, θ_s and θ_L are supplied to analog to digital converter 44. This circuit converts these signals into appropriate digital representations thereof. It will be recalled that these signals were supplied from the downhole equipment in the form of frequency modulated signals each of which operated within a separate relatively narrow frequency band. Thus, five output signals from analog to digital converter 44 representative of the five quantities R_i, R_{xo}, d_i, θ_s and θ_L are furnished to the general purpose digital computer 45 which may be of the type previously described. The computer 45 then correlates these measurements in the manner previously discussed with respect to Figure 2 to derive signals representative of the percentage of oil saturation, ε_{xo}, ε_t, R_t, R_{xo} and d_i. These outputs are supplied to a recorder 46, which may be of a type conventional in the art such as a strip chart of film chart recorder, where they are recorded as a function of bore hole depth. The depth information is supplied from the sheave wheel 16 which is electrically or mechanically linked to the computer 45 and the recorder 46 for this purpose.

WHAT WE CLAIM IS:—

1. A method for determining the dielectric constant ε_{xo} of the invaded zone and the dielectric constant ε_t of the uninvaded formations in respect of earth formations invaded by conductive drilling fluid from a well borehole, said method comprising:

determining by induction and resistivity well logging the resistivity R_{xo} of the invaded zone, the resistivity R_t of the uninvaded formation and the radial depth of invasion d_i, all at a determined depth in the well bore;

transmitting electromagnetic waves at a frequency in the range of 10 to 60 megahertz from a transmitter coil in the borehole;

measuring the phase shift of said waves between the two coils of a first pair of spaced receiver coils at a first longitudinal distance from said transmitter coil and generating a signal θ_s representative thereof, said first distance providing a first radial depth of investigation substantially in said invaded zone;

measuring the phase shift of said waves between the two coils of a second pair of spaced receiver coils at a second longitudinal distance from said transmitter coil and generating a signal θ_L, said second distance between greater than said first distance to provide a second radial depth of investigation substantially in said uninvaded formation; and

for said set of determined resistivity R_{xo}, resistivity R_t and invasion depth d_i, correlating the signals θ_s and θ_L to derive indications of the dielectric constants ε_{xo} and ε_t at said depth.

2. A method as claimed in Claim 1 wherein said steps are performed at a plurality of determined bore hole depths to derive indications of ε_{xo} and ε_t as a function of borehole depth.

3. A method as claimed in Claim 2 wherein said steps are performed substantially continuously with changing borehole depth to derive indications of ε_{xo} and ε_t as a function of borehole depth.

4. A method as claimed in any one of Claims 1 to 3 including recording the representations of R_{xo}, R_t, d_i, ε_{xo}, and ε_t as a function of borehole depth.

5. A method as claimed in any one of Claims 2 to 4 including determining the porosity ϕ of the earth formations surrounding the borehole as a function of borehole depth; and

combining the porosity and the indications of ε_{xo} and ε_t as a function of borehole depth according to a predetermined relationship to derive an indication of the percentage of movable hydrocarbon in the earth formations surrounding the well bore as a function of borehole depth.

6. A method as claimed in Claim 5 including the step of recording the indication of movable hydrocarbon as a function of borehole depth.

7. A method as claimed in any one of

Claims 1 to 6 wherein the two coils of said second pair are further apart from one another longitudinally of the borehole than are the two coils of said first pair.

8. A method as claimed in Claim 7 wherein the coils of said first pair are spaced apart by substantially 15 cm. and wherein the coils of the second pair are spaced apart by substantially 30 cm.

9. A method as claimed in any one of Claims 1 to 8 wherein the nearer coil of said first pair is substantially 25 cm. from said transmitter coil, and wherein the nearer coil of said second pair is substantially 76 cm. from said transmitter coil.

10. A method as claimed in any one of Claims 1 to 9 wherein said electromagnetic waves are transmitted at a single frequency of substantially 30 megahertz.

11. A method for determining the dielectric constant ε_{xo} of the invaded zone and the dielectric constant ε_t of the uninvaded formations in respect of earth formations invaded by conductive drilling fluid from a well borehole, said method being substantially as described herein with reference to the accompanying drawings.

MICHAEL BURNSIDE & PARTNERS,
Chartered Patent Agents,
Hancock House,
87 Vincent Square,
London, SW1P 2PH.
Agents for the Applicants.

Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1979
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

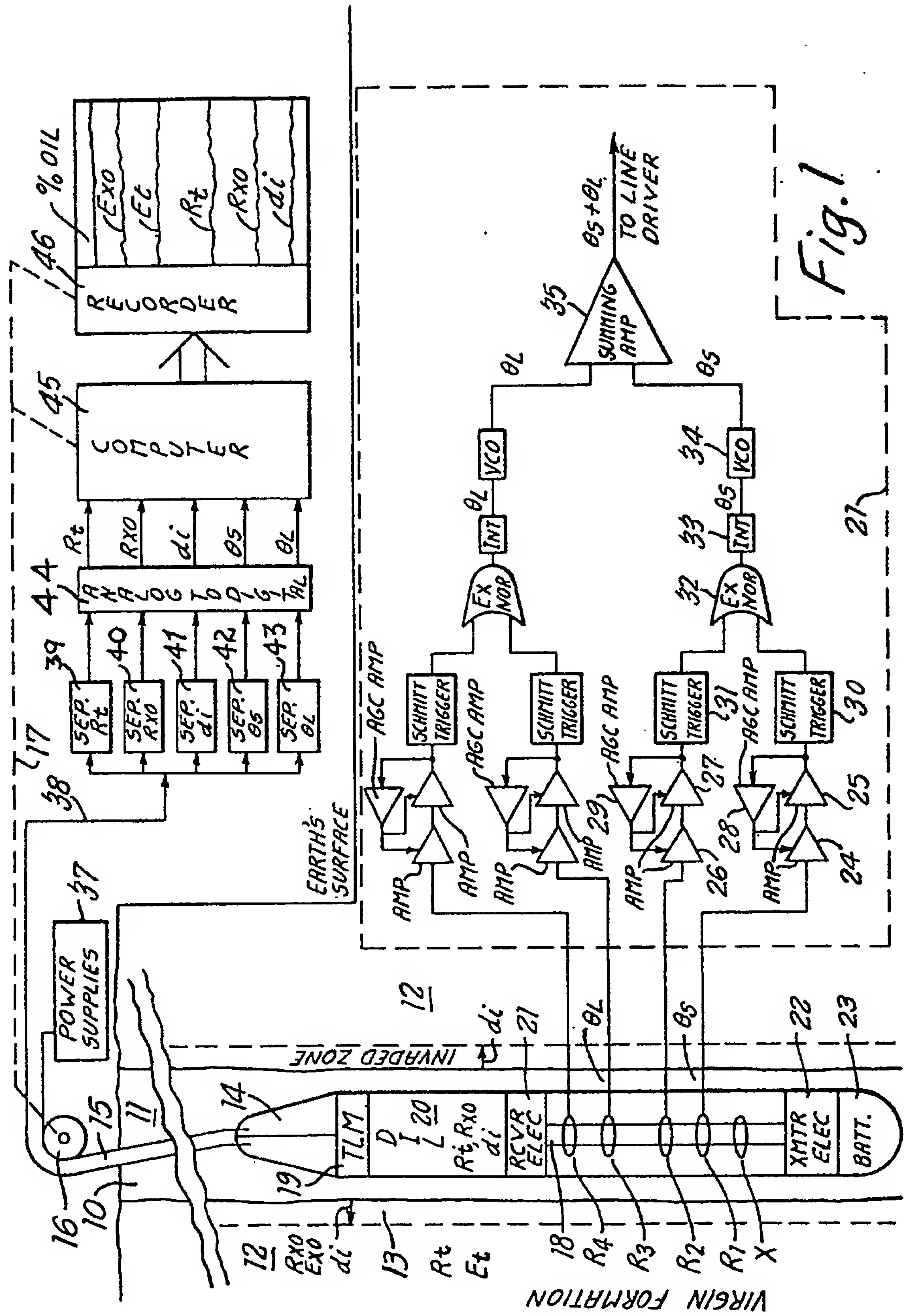
RECORDER
% OIL
Exo
Et
Rt
Rxo
di
COMPUTER
ANALOG TO DIGITAL
SEP. Rt
SEP. Rxo
SEP. di
SEP. θS
SEP. θL
POWER SUPPLIES
EARTH'S SURFACE
AGC AMP
AMP
SCHMITT TRIGGER
EX NOR
INT
VCO
SUMMING AMP
θS+θL
TO LINE DRIVER
INVADED ZONE
VIRGIN FORMATION
TLM
DIL
RCVR ELEC
XMTR ELEC
BATT.

Fig. 1

1 539 222 COMPLETE SPECIFICATION
2 SHEETS

This drawing is a reproduction of the Original on a reduced scale.
SHEET 2

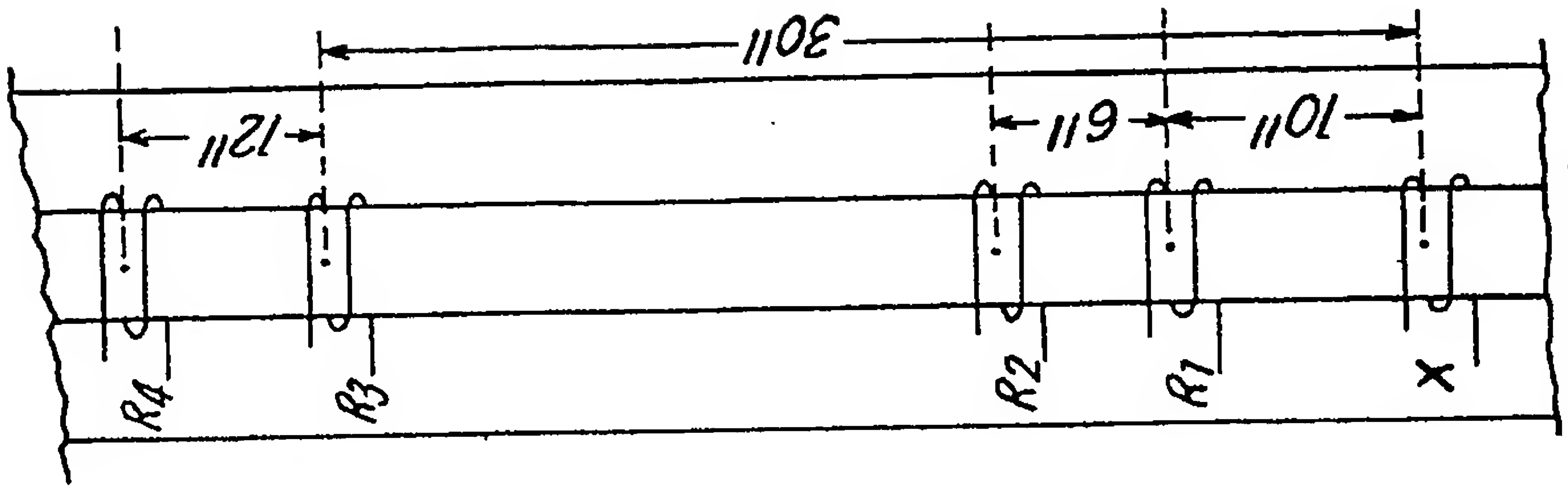

Fig. 3

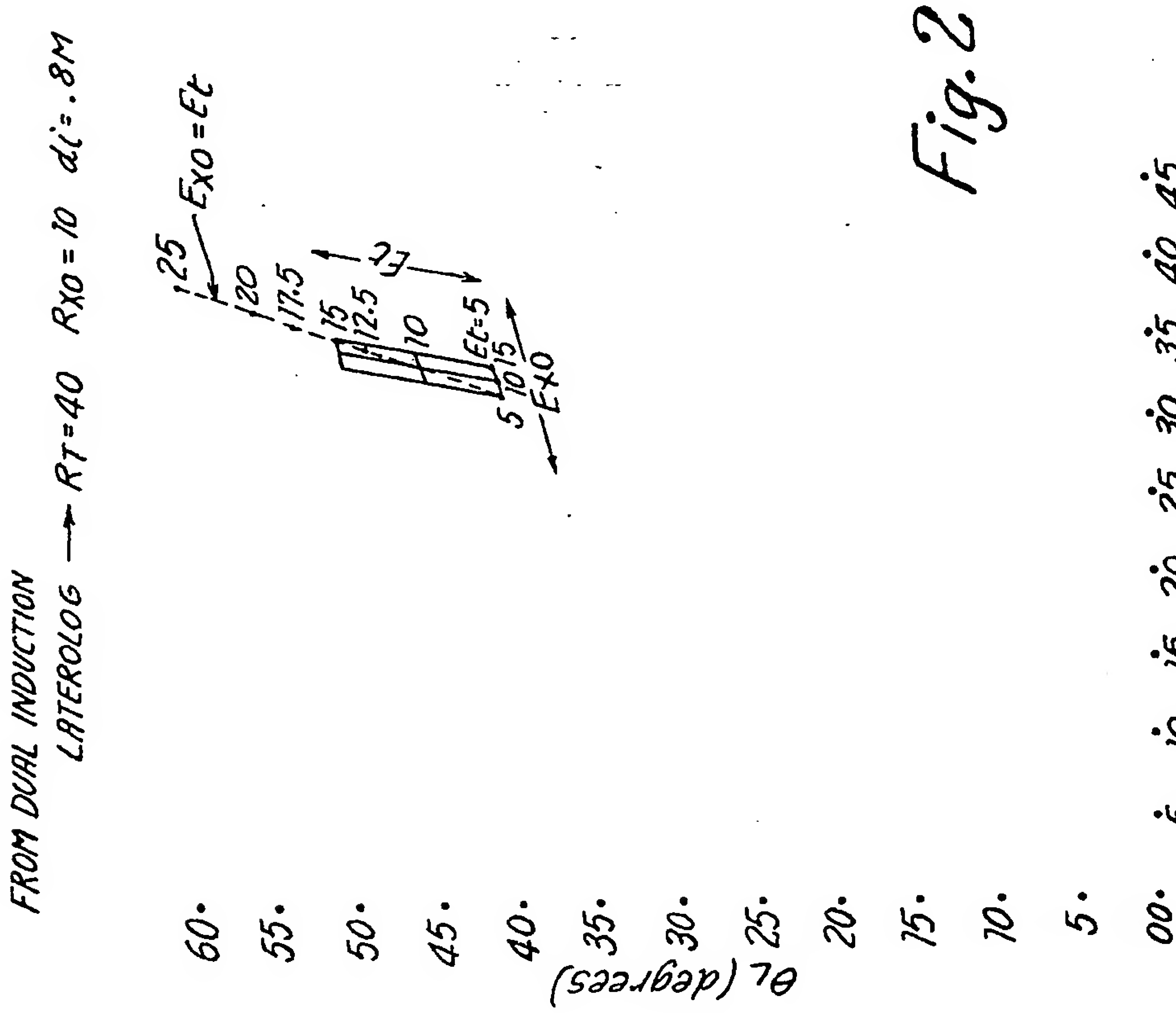

Fig. 2